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(54) **ADVANCED VOLUME GAUGING DEVICE**

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G01F 17/00 (2006.01)

(52) **U.S. Cl.** .... **73/290 B**; 73/149

(58) **Field of Classification Search** .... 73/290 B, 73/149

See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

3,895,519 A		7/1975	Bouchy et al.	73/149
4,840,064 A	*	6/1989	Fudim	73/290 B
4,987,775 A		1/1991	Chobotov	73/149
5,531,111 A		7/1996	Okamoto et al.	73/149
5,880,356 A		3/1999	Delepierre-Massue et al.	73/37

FOREIGN PATENT DOCUMENTS

FR	2682185	4/1993

* cited by examiner

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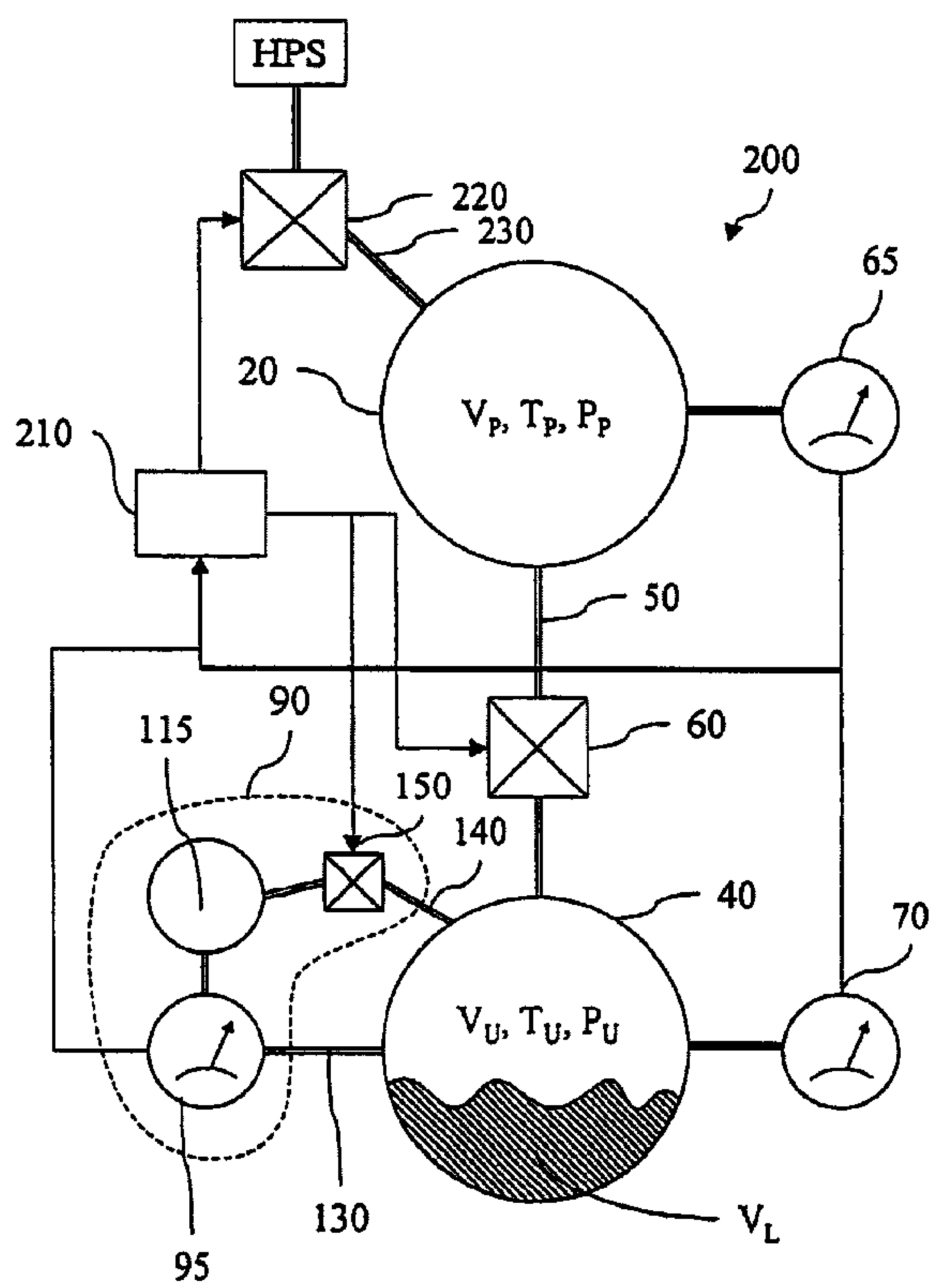
(57) **ABSTRACT**

A new high precision volume gauging system for measuring the volume of a propellant VL enclosed at a first pressure PU within a propellant tank **(40)** of a volume VT. The improved precision compared with prior art is achieved in that it comprises a high precision pressure sensor **(90)** which is comprised of a reference chamber **(115)** that is connected to the propellant tank **(40)** by a communication line **(140)**, a valve **(150)** for controlling the gas flow through the line **(140)**, and a high precision differential pressure sensor **(95)** that is arranged to record the pressure difference between the reference chamber **(115)** and the propellant tank **(40)** to which it is connected through a communication line **(130)**.

7 Claims, 5 Drawing Sheets



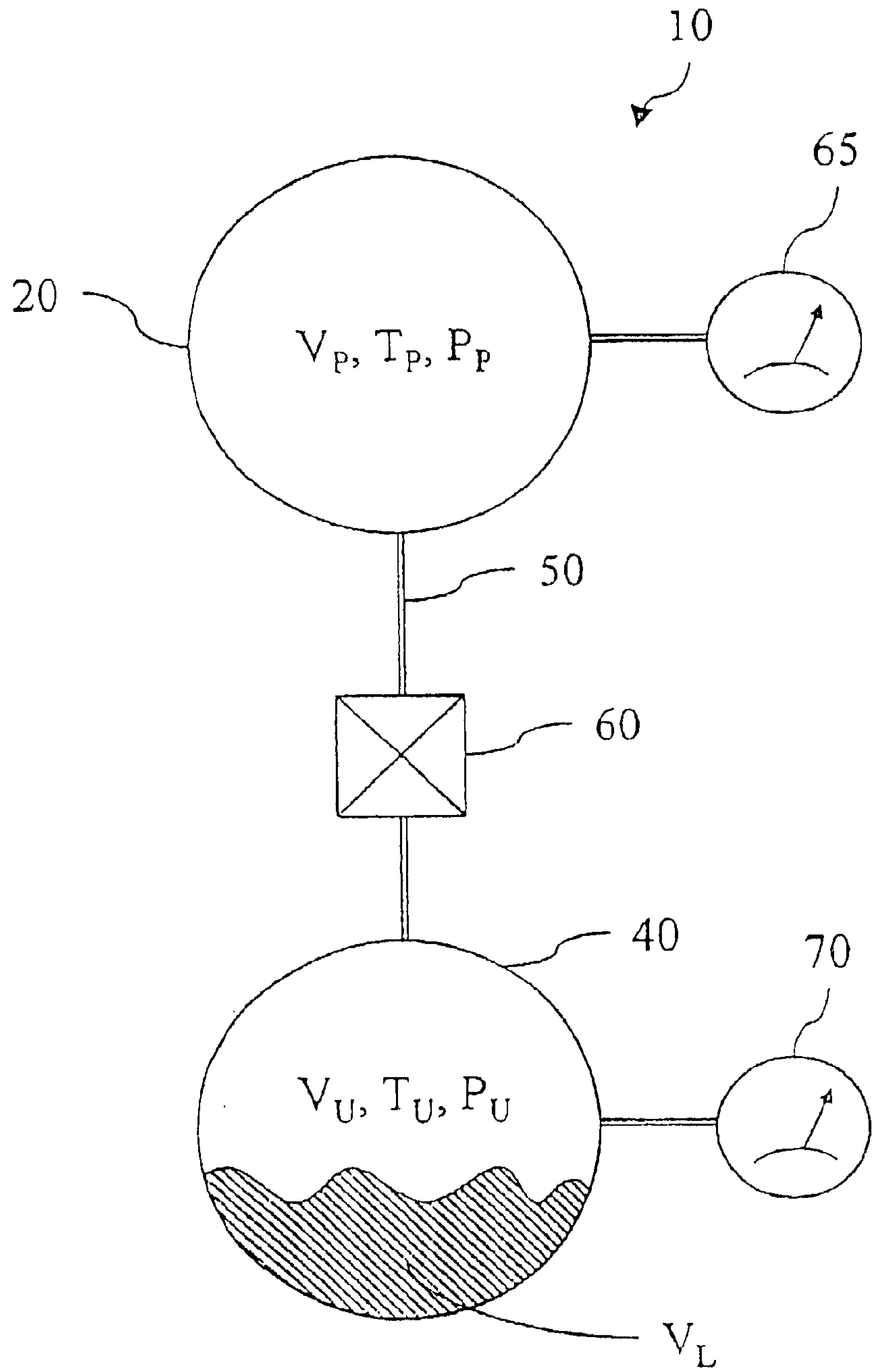


Fig. 1

Prior Art

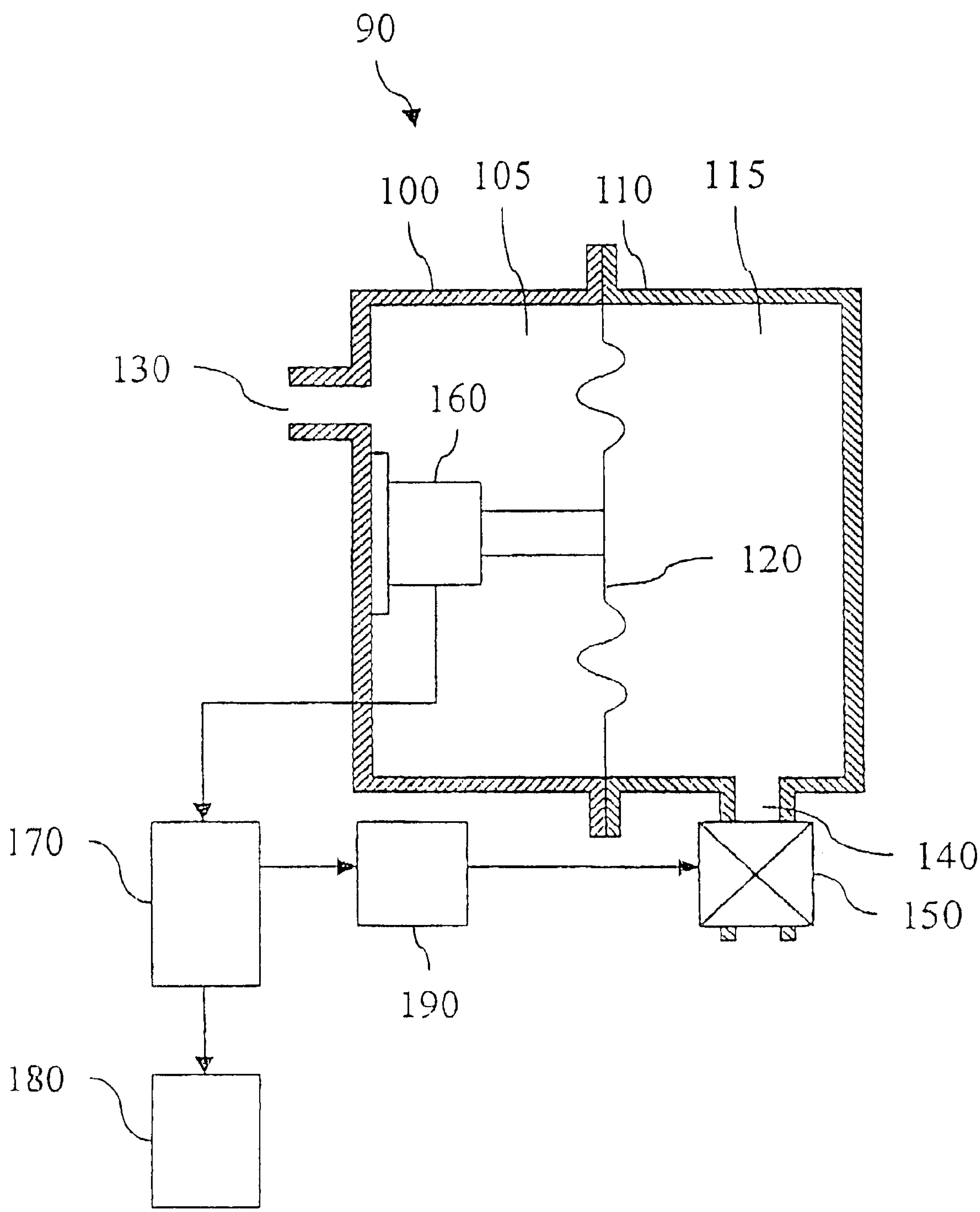


Fig. 2

Prior Art

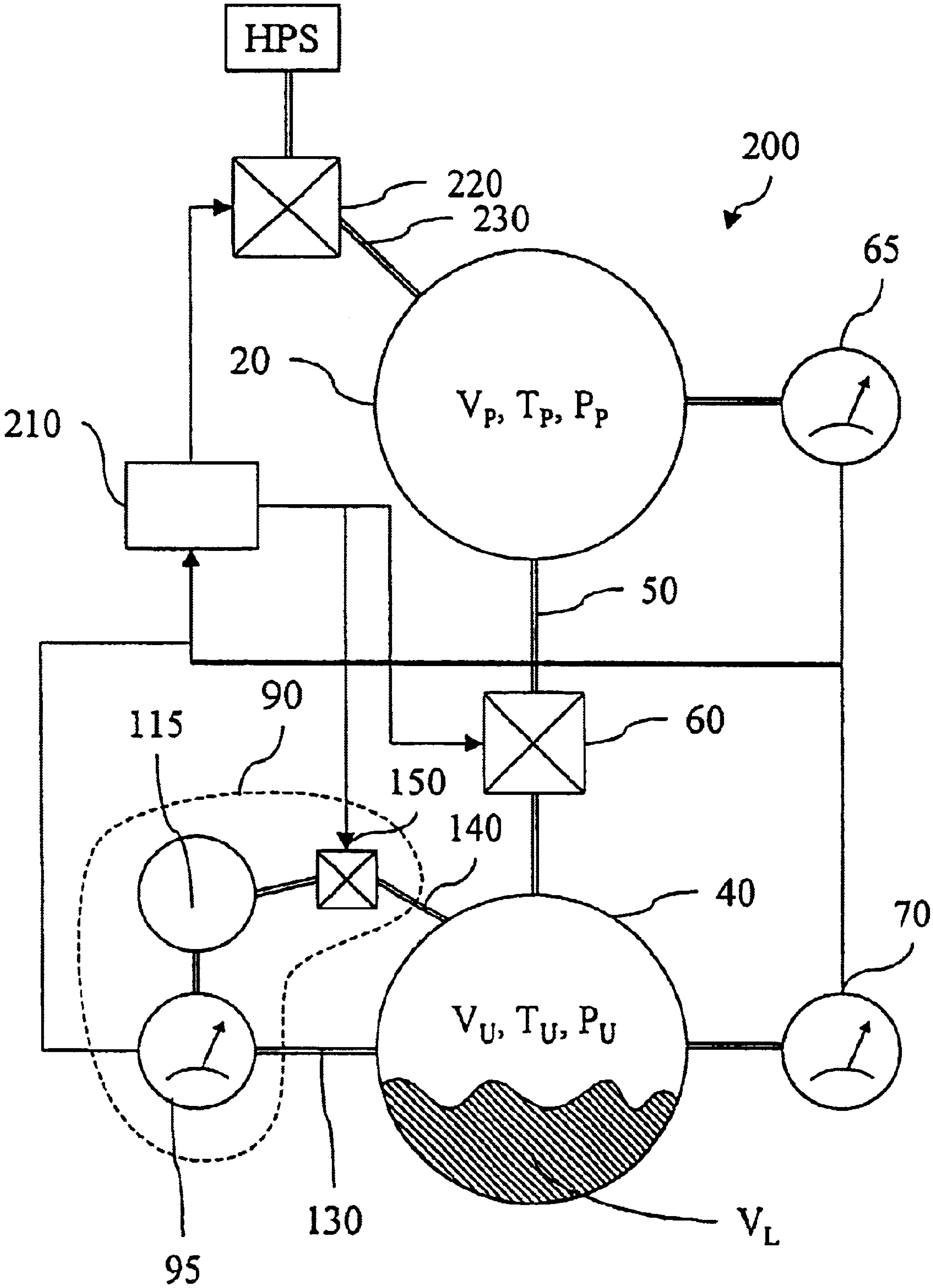

HPS
200
220
230
65
20
V_P, T_P, P_P
210
50
90
60
115
150
140
40
70
V_U, T_U, P_U
130
95
V_L

Fig. 3

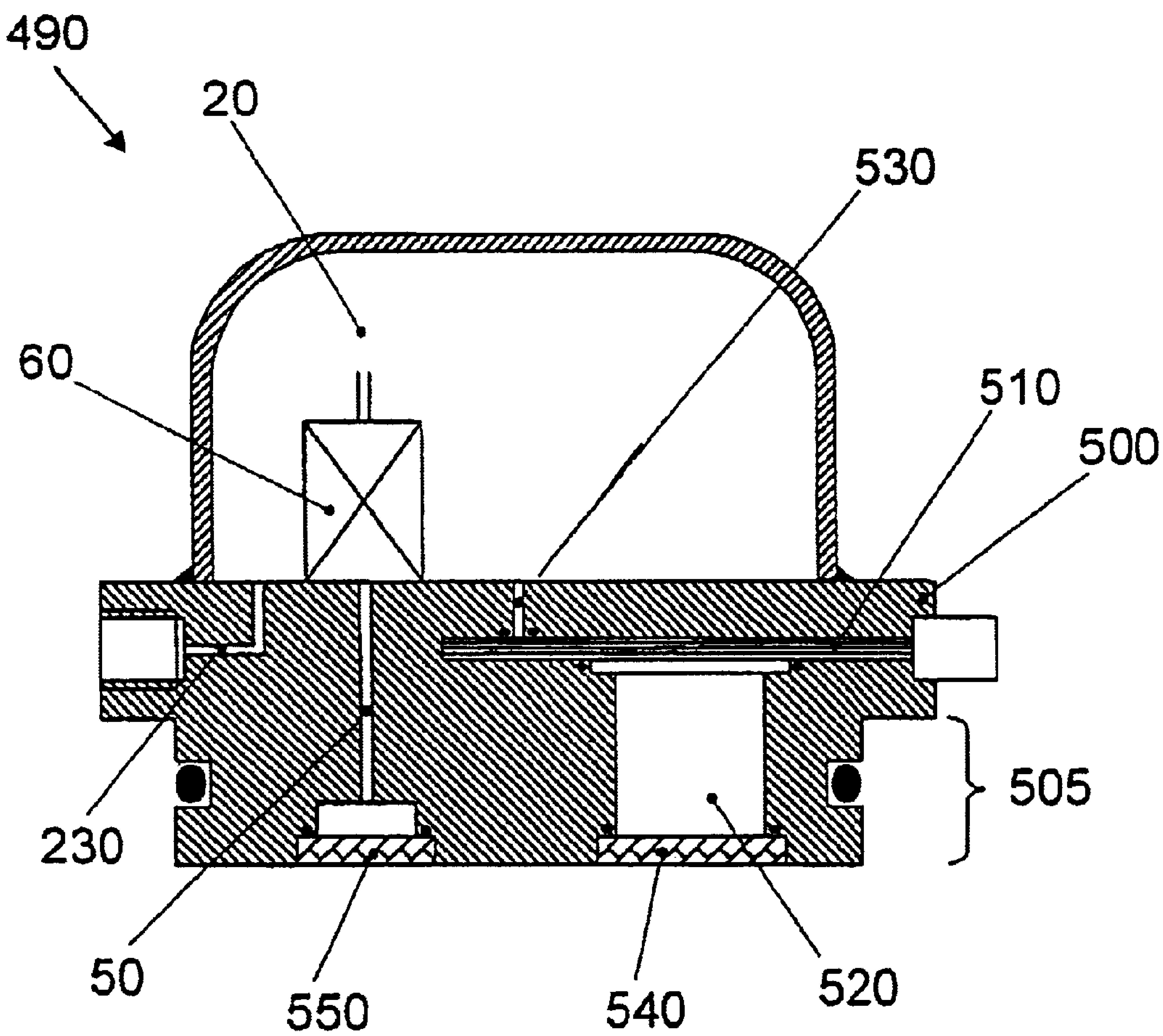


Fig. 4

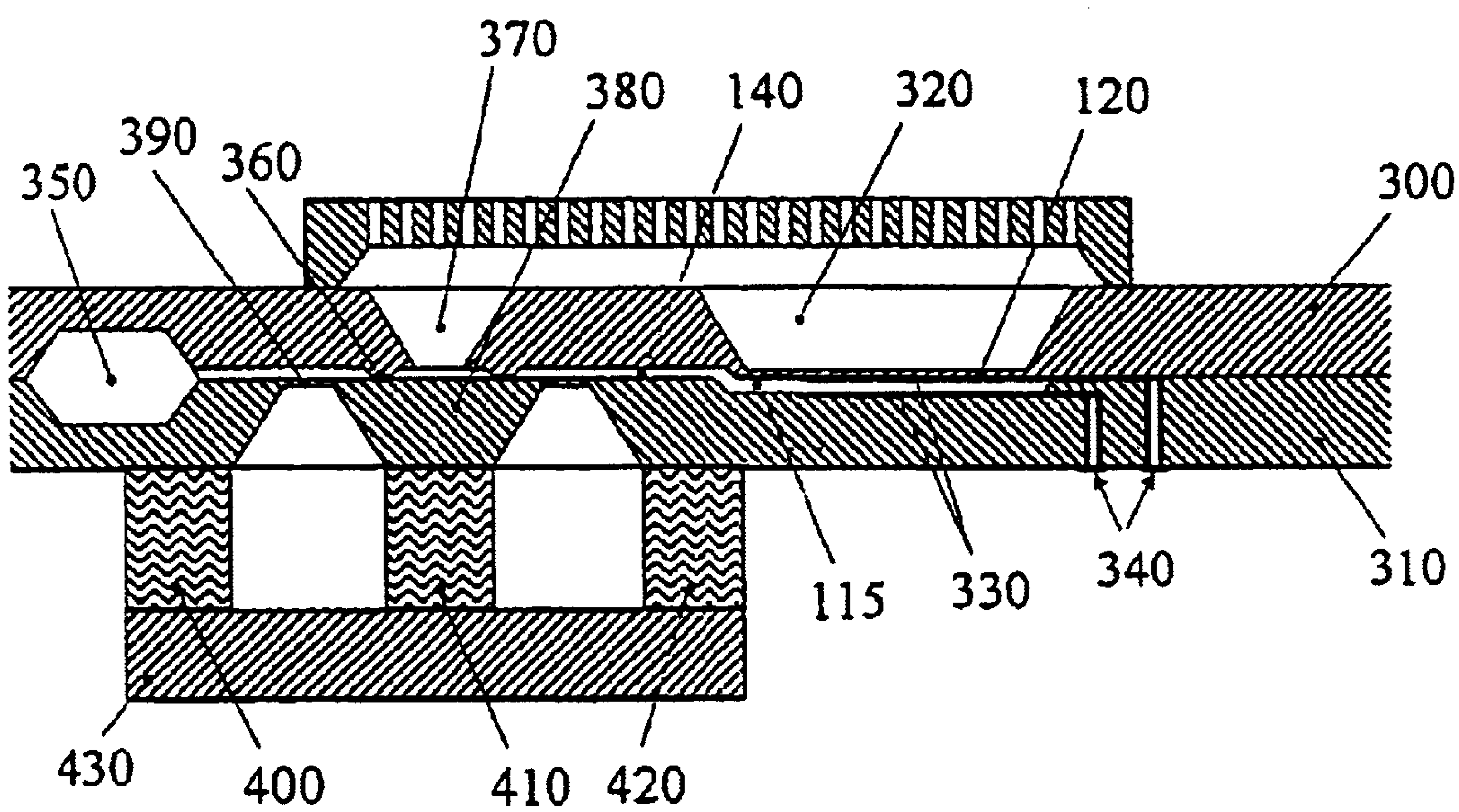

370
380
140
320
120
390
360
350
300
115
330
340
310
430
400
410
420

Fig. 5

ADVANCED VOLUME GAUGING DEVICE

FIELD OF THE INVENTION

The present invention relates to an advanced volume gauging device. More specifically, the invention relates to a high precision miniaturized volume gauging device.

PRIOR ART

It is a well-known problem to measure the amount of remaining propellant in a tank in zero gravity environments. The reason is that in the absence of gravity, the liquid will float around freely inside the tank. Significant benefits can be obtained by developing reliable volume gauging systems with better accuracy.

For a communication satellite in geosynchronous orbit, only 10% uncertainly in the estimation of remaining propellant, which is not uncommon, can lead to that more than a year of the satellite life is lost. This leads to a very high cost penalty due to the estimate error, keeping in mind the huge cost for a communication satellite.

In U.S. Pat. No. 4,987,775 Chobotov et al disclose a volume gauging system based on thermodynamic principles. This system **10** is shown in FIG. **1**, and it includes a pressurisation tank **20** of volume V_p. The tank **20** includes a pressurisation gas at pressure P_p and temperature T_p. The system **10** further includes a propellant tank **40** of volume V_T. The tank **40** includes a generally liquid propellant occupying a volume V_L. The portion of the tank **40** unoccupied by the liquid phase of the propellant has an ullage volume V_u, a pressure P_u and a temperature T_u. The tanks **20** and **40** are interconnected by a gas line **50**. Gas flow through the line **50** is controlled by an injection valve **60**. Additionally, the pressure P_p within the tank **20** is monitored by a first absolute pressure transducer **65** in communication therewith. Similarly, a second absolute pressure transducer **70** monitors the pressure P_u within the ullage volume V_u of the tank **40**. The temperatures T_p and T_u of the tanks **20** and **40** are ascertained by temperature sensors (not shown) operatively coupled thereto.

The propellant measurement system **10** is adapted to determine the ullage volume V_u of the tank **40** and thereby determine the volume of remaining propellant V_L through the expression $V_L=V_T-V_u$. The ullage volume V_u is determined in the following manner. First, the pressure P_p is chosen to be larger than the pressure P_u in order that the pressurisation gas within the tank **20** flows into the tank **40** upon opening of the valve **60**. The valve **60** is opened until a suitably measurable increase occurs in the pressure P_u within the chamber **40**. The valve **60** is then closed and the changes in the pressures P_p and P_u are determined from the pressure transducers **65** and **70**. The ullage volume V_u may now be determined by noting that during the above process gas is conserved within the system **10**. Accordingly, from fundamental thermodynamic equations assuming an isothermal process and that the propellant is incompressible:

$$\frac{P_pV_p}{T_p}+\frac{P_uV_u}{T_u}=\frac{(P_p-dP_p)V_p}{T_p}+\frac{(P_u+dP_u)V_u}{T_u} \qquad [1]$$

where

dP_p=the change in P_p as measured by the first pressure transducer **65**.

dP_u=the change in P_u as measured by the second pressure transducer **70**.

After simple algebra,

$$\frac{dP_pV_p}{T_p}=\frac{dP_uV_u}{T_u} \qquad [2]$$

Hence,

$$V_u=\frac{dP_pV_pT_u}{dP_uT_p} \qquad [3]$$

From which the volume of propellant remaining in the tank **40** may be expressed as:

$$V_L=V_T-V_u=V_T-\frac{dP_pV_pT_u}{dP_uT_p} \qquad [4]$$

To achieve results with high accuracy when the tank **40** is nearly empty, dP_u has to be recorded with very high requirement on resolution over a pressure range from a few bars up to 22 bars. No commercially available pressure sensor meets the requirements. Among space qualified sensors, the performance of best sensors is far from the requirements. The traditional approach is to take a good sensor and then improve the performance with new signal conditioner electronics where the rapid technological progress permits new designs with higher performance. This approach will probably not work in this case, as error sources in the sensor internal design become dominant. The errors may be of several types, long term drift, linearity, hysteresis, etc. This indicates that an alternative sensor concept must be used, which is directly tailored for the dP_u applications.

One possible way to accomplish such a sensor is described in JP 57035743, and shown in FIG. **2**. This particular sensor **90** is intended for measuring small fluctuations in atmospheric pressure, and is constructed as follows. A space which has been surrounded by a first vessel **100** and a second vessel **110** is divided into two parts by a flexible film body **120**, and a first chamber **105** and a reference chamber **115** are formed by the flexible film body **120** and the vessel **100**, and the flexible film body **120** and the vessel **110**, respectively. On the vessel **100** and the vessel **110** are provided communicating holes (or lines) **130**, **140** by which the respective chambers **105**, **115** communicate to the open air, and on the communicating hole **140** is provided an electromagnetic valve **150** for opening and closing between the reference chamber **115** and the open air. A pressure sensor **160** detects and measures pressure of a difference between the chamber **105** and **115** through the flexible film body **120**. A measuring signal processing part **170** receives a signal which has been sent from the pressure sensor **160**, converts it to a variation of pressure by means of signal processing, sends it out to a display recording part **180**, also sends out an opening and closing indication signal to an opening and closing means driving part **190** whenever a variation of pressure attains to a set value, and instantaneously opens the electromagnetic valve **150**. Generally, the concept of this sensor may be described as a differential pressure sensor **95** measuring a pressure difference between the closed reference chamber **115** and the surrounding atmosphere.

The sensor concept presented in JP 57035743 may be designed such that a huge increase in sensitivity (in a limited but selectable range) is achieved, compared to a conventional differential pressure sensor. A numerical example gives the following results. The pressure on the frontside and the backside will be absolutely equal if the valve **150** is open long enough. The pressure in reference chamber **115** should be within 0.1% of 22 bars if the tank pressure is 22 bars. Assume that the pressure sensor membrane **120** has 100-mbar sensitivity for a full-scale deflection and that the deflection may be measured with 0.1% accuracy. The end result is that with an absolute pressure of 22 bars a pressure change of 0.022 mbar can be detected. The resolution is 10^{-6}, which is far beyond what can be achieved with any conventional pressure sensor today.

SUMMARY OF THE INVENTION

The present invention aims toward a self-contained miniaturized volume gauging device, which can be mounted on/inside, the tank wall. Such a device has three major advantages compared with existing systems. Firstly, the sample volume will have the same temperature as the tank volume, which relaxes the temperature measurement requirements. Secondly, the propellant tank walls provide additional radiation shielding for the integrated electronics. Thirdly, the proposed device will be both lighter and smaller compared with conventional systems. The device shall include the sample volume, gas injection system, super-high precision pressure sensor and electronics for control, signal conditioning and digital interface to the spacecraft.

An object of the present invention therefore is to provide a new miniaturized volume gauging system.

Another object of the present invention is to provide a new method for measuring the remaining fuel in a propellant tank using a dP pressure sensor.

These objects and other objects of the invention are achieved by the volume gauging device and the method as defined in the claims.

BRIEF DESCRIPTION OF THE FIGURES

FIG. **1** schematically shows an existing propellant gauging system.

FIG. **2** shows an existing high precision pressure sensor.

FIG. **3** schematically shows a propellant gauging system according to the present invention.

FIG. **4** shows one embodiment of the miniaturized fuel gauging device of the invention.

FIG. **5** shows one embodiment of a micromechanical dP sensor according to one embodiment of the invention.

DETAILED DESCRIPTION OF THE INVENTION

Embodiments of the invention will now be described with reference to the figures in which members having the same function as in prior art will be given the same number.

FIG. **3** shows a block diagram of one embodiment of the invention. The fuel gauging system **200** comprises all parts shown in FIG. **1**, and one high precision pressure sensor **90** according to FIG. **2**, which pressure sensor **90** is coupled to the propellant tank **40** by the communicating holes **130**, **140**. The system further comprises a processing/control unit **210** for calculating the volume of the remaining fuel VL and controlling the gauging cycle. A line **230** connects the pressurisation tank **20** with a high pressure source (HPS) and the loading of high pressure gas into the pressurisation tank **20** is controlled by a valve **220**.

The system may further comprise filters to prevent liquids inside the gas system and temperature sensors for measuring the temperatures in the pressurisation tank **20** and the propellant tank **40**. But as the present invention aims toward a miniaturized fuel gauging device, which can be mounted on/inside the tank wall, the gas in the pressurisation tank **20** will approximately have the same temperature as the gas in the propellant tank **40**, whereby the temperature measurements may be omitted.

When a determination of remaining propellant shall be performed the following sequence is activated by the processing/control unit **210**. Valve **220** is opened and the pressurisation tank **20** is filled with gas to a high pressure (P_p), then the valve **220** is closed and the pressure transducer **65** registers the pressure Pp. At the same time absolute pressure (P_u) is registered in the propellant tank **40** by the pressure transducer **75**, and the valve **150** is closed such that the reference chamber **115** will remain at the pressure P_u. Thereafter the injection valve **60** is opened and the high pressure gas from the pressurisation tank **20** is injected into the propellant tank **40**. The high precision pressure sensor **90** registers the resulting small increase of the absolute pressure dP_u in the propellant tank **40**, the injection valve **60** is closed and the processing/control unit **210** calculates the volume of the remaining propellant using equation [5] below. As the pressure in the pressurisation tank **20** now is equal to the pressure in the propellant tank **40**, dP_p in equation [4] may be replaced by $(P_p-(P_u+dP_u))$ whereby:

$$V_L = V_T - V_u = V_T - \frac{(P_p - (P_u + dP_u))V_p T_u}{dP_u T_p} \quad [5]$$

When a volume gauging system is installed in/on a propellant tank, it will also replace the usual pressure measurements for tank monitoring. Thus, the pressure measurement system shall enable two kinds of pressure data, dP_u pressure valves for volume gauging and absolute tank pressure for house-keeping

Requirements on a volume gauging system may be:

Tank volume:	10-T.B.D. liter
P_u measurements:	pressure range 2–22 bar
	resolution 0.01 bar
	accuracy 0.1%
dP_u measurements:	diff. pressure range ±100 mbar
	resolution 0.1 mbar
	accuracy 0.1% with ±0.1 bar range
	response time <100 mS
	sampling rate 5 s/s
P_p measurements:	pressure range 10–200 bar
	resolution 0.1 bar
	accuracy 0.1%

The requirements on fast response time and sampling rate originates from the fact that the tank pressure value are of significant importance for the accuracy of the dP_u measurement after a gas sample injection. The pressure conditions are not in steady state conditions.

FIG. **4** shows an exemplary embodiment of a self-contained miniaturized volume gauging device **490**, which is intended to be mounted directly on the tank wall. This embodiment comprises a main body **500** on which a pressurisation tank **20** is arranged.

The main body **500** comprises a communication portion **505** that is arranged to mate a hole in the wall of a propellant tank **40**. An injection valve **60** is mounted on the main body **500** inside the pressurisation tank **20**. A first line **230** extends from an outer surface of the main body **500** to the pressurisation tank **20**, through which first line **230** loading of high-pressure gas into the pressurisation tank **20** is performed. A high-pressure valve **220** (not shown in the figure) is in this embodiment arranged separately from the volume-gauging device **490** and connected to the line **230**. A second gas line **50** extends through the main body **500** terminating at one end in the propellant tank **40** and at the other end at the injection valve **60**. A micromechanical pressure sensor unit **510** is arranged in the main body **500**. The pressure sensor unit **510** comprises one P_u sensor, one P_p sensor and one dP_u sensor. The P_u sensor and the dP_u sensor communicates with the propellant tank **40** via a third gas line **520**, and the P_p sensor communicates with the pressurisation tank **20** via a fourth gas line **530**. An electrical connector for connecting the pressure sensor unit **510** and the injection valve **60** to an external control unit (not shown), is arranged on the side of the main body **500**. To prevent propellant from entering the lines **520** and **50**, they are each provided with a protection filter **540** and **550** respectively. FIG. **5** further shows a number of sealing rings that prevent gas or propellant leakage in the system.

In addition to the vastly increased sensitivity, the proposed self-contained miniaturized volume gauging device **490** is considerably smaller and lighter than existing systems built up from discrete components. However, for micro-satellites and the like, even smaller devices are needed, and as the propellant tank **40** in such systems is much smaller, the pressurisation tank **20** may be extremely small, a self-contained all micromechanical volume gauging device may be applicable.

A practical realisation of a micromechanical dP-sensor which may be used in the above embodiments is shown in FIG. **5**. The P_u sensor and the P_p sensor of the micromechanical pressure sensor unit **510** are not shown here, as they may be considered trivial to one skilled in art. This dP-sensor is based on bonded micromachined wafers. The material is most likely silicon but other more corrosion resistant materials such as quartz or silicon carbide can also be used. The device works as follows. Wafer A **300** and wafer B **310** form the pressure sensor and the valve elements. A large cavity **320** is formed on wafer A **300** by suitable etching methods. The bottom of the cavity becomes a flexible membrane **120**. Two metal planes **330** or electrodes between wafer A **300** and B **310** act as a capacitor where the capacitance changes when the membrane bends. The electrodes can be accessed via two through-plated holes **340**. This is the pressure sensor part.

A reference chamber **115** is connected to the valve through a small channel **140**. The volume of the reference chamber **115** is much larger than expected as it also is connected to a buffer volume **350**. This volume has two good effects on the system. It reduces the sensitivity for valve leakage during the measurement period and also the effects of the flexible membrane **120** deflection which otherwise could cause a small increase of the locked reference pressure. A valve seat **360** is formed in wafer A **300** through wet etching of a shallow cavity with a ringshaped ridge. The gas entrance is through a wet etched through hole **370**. The hole is etched from the outside. A valve cap **380** is formed in wafer B **310**, it is a square shaped block suspended all around by a thin flexible membrane **390**. The valve cap **380** may be moved against or from the valve seat by changing the length of valve actuators **400, 410, 420**. The actuators **400, 410, 420** may be piezoelectric elements where the total length can be changed by a control voltage. The valve cap **380** opens when the central actuator **410** contracts or when the surrounding actuators **400, 420** elongate. The central actuator **410** is mechanically connected to the surrounding by use of a third silicon wafer **430**.

A fourth silicon wafer **440** with a filter structure protects the fragile sensor membrane **120** from liquids or particles.

What is claimed is:

1. A method of measuring the volume of a propellant V_L enclosed at a first pressure P_U within a first tank of a first volume V_T, where the tank volume V_T is equal to the volume of the propellant V_L plus an ullage volume V_U, said method comprising the steps of:

(a) enclosing a pressurization gas of a second volume V_p in a second tank at a second pressure P_p, said second pressure P_p being greater than said first pressure P_U;

(b) opening a connection between the ullage volume in the first tank and a reference chamber such that the reference pressure P_r will be essentially equal to P_U;

(c) closing the connection between the ullage volume in the first tank and a reference chamber such that the reference pressure P_r will be independent of P_U;

(d) opening a connection between the first tank and the second tank;

(e) measuring the resulting pressure difference dP_U between the ullage volume and the reference chamber using a differential pressure (dP) sensor of high accuracy;

(f) calculating the ullage volume V_U of said first tank in accordance with the following equation:

$$V_u = \frac{(P_p - (P_u + dP_u))V_p}{dP_u};$$

and

(g) subtracting said ullage volume V_U from said first V_T volume to determine said propellant volume V_L.

2. The method of claim **1**, characterised in that it comprises the step of:

measuring the temperatures of said ullage volume T_U and said pressurization gas T_p, and that the step of calculating the ullage volume V_U of said first tank is performed in accordance with the following equation:

$$V_u = \frac{(P_p - (P_u + dP_u))V_p T_u}{dP_u T_p}.$$

3. High precision volume gauging system for measuring the volume of a propellant V_L enclosed at a first pressure P_U within a propellant tank **(40)** of a volume V_T, said system comprising a pressurisation tank **(20)** that is connected to a high pressure source by a high pressure gas line **(230)** and to the propellant tank **(40)** by a line **(50)**, an injection valve **(60)** controlling the gas flow through the line **(50)**, a first absolute pressure transducer **(65)** for monitoring the pressure P_p within the tank **(20)**, and a second absolute pressure transducer **(70)** monitoring the pressure P_u within the ullage volume V_u of the tank **(40)**, wherein the system further comprises a high precision pressure sensor **(90)** which is comprised of a reference chamber **(115)** that is connected to the propellant tank **(40)** by a communication line **(140)**, a valve **(150)** for controlling the gas flow through the line **(140)**, and a high precision differential pressure sensor **(95)** that is arranged to record the pressure difference between the reference chamber **(115)** and the propellant tank **(40)** to which it is connected through a communication line **(130)**.

4. High precision volume gauging system according to claim **3**, provided as a self-contained miniaturized volume gauging device **(490)** that is arranged to be mounted directly on the wall of the propellant tank **(40)**.

5. Self-contained miniaturized volume gauging device **(490)** according to claim **4**, wherein the high precision pressure sensor **(90)** is provided as a micromechanical pressure sensor unit **(510)**.

6. Self-contained miniaturized volume gauging device **(490)** according to claim **5**, wherein the micromechanical pressure sensor unit **(510)** further comprises the first absolute pressure transducer **(65)**, the second absolute pressure transducer **(70)**.

7. High precision micromechanical pressure sensor unit **(510)** according to claim **5**, comprised of a first wafer A **(300)** which is bonded to the top surface of a second wafer B **(310)**, wherein the differential pressure sensor **(95)** is formed in that, a deep cavity **(320)** is formed in the top surface of wafer A **(300)** such that a flexible membrane **(120)** is formed by bottom of the cavity **(320)** and the bottom surface of wafer A **(300)**, a reference chamber **(115)** is formed in the wafer B **(310)** beneath the flexible membrane **(120)**, metal electrodes **(330)** are arranged at the bottom surface of the flexible membrane **(120)** and the bottom surface of the reference chamber **(115)** such that they act as a capacitor where the capacitance changes when the membrane bends, wherein the valve **(150)** is comprised of a valve seat **(360)** in the shape of a ring-shaped ridge formed in the bottom surface of wafer A **300**, a gas entrance **(370)** located inside the valve seat **(360)**, a valve cap **(380)** formed in the top surface of wafer B **310** as a rigid cap portion surrounded by a thin flexible membrane **(390)**, the valve cap **(380)** is closed and opened by a piezoelectric actuator arrangement **(400, 410, 420)**, and wherein the reference chamber **(115)** is connected to the valve through a small channel **(140)**.

* * * * *